Seismic Performance Evaluation of Steel Moment Frames with Slit-Friction Hybrid Dampers

Hyunkoo Kang, Joonho Lee, and Jinkoo Kim

***Abstract*—** This study investigates the seismic energy dissipation capacity of a hybrid passive damper composed of a friction and a hysteretic slit damper. The capacity of the hybrid device required to satisfy a given target performance of a reinforced concrete moment resisting frame designed with reduced design base shear is determined based on the ASCE/SEI 7-10 process, and the seismic performances of the structures designed without and with the hybrid dampers are verified by nonlinear dynamic analyses.

***Index Terms*—** Hybrid dampers, Slit dampers, Friction dampers, Seismic performance.

I. Introduction

The seismic performances of hysteretic passive energy dissipative devices have been investigated such as slit dampers [1], friction dampers [2], and buckling restrained braces [3]. Tremblay et al. [4] carried out comparative study of tied braced frames with three types of energy dissipation devices such as friction dampers, buckling restrained bracing members, and self-centering energy dissipative devices..

This study developed a hybrid passive energy dissipation device composed of a friction damper combined with a steel plate slit damper. The hybrid damper has an advantage in that only a friction damper is activated for wind load or small earthquakes, and combined action of a friction damper and a hysteretic damper is induced for strong earthquakes. The residual displacement in the friction dampers caused by strong wind or small earthquakes can be recovered by the structure and the slit dampers which still remain elastic and provide restoring force for the friction dampers. For seismic design and retrofit of a structure, the capacity of the hybrid device to satisfy a given target performance was determined based on the ASCE/SEI 7-10 process. The effect of the device was verified by nonlinear time-history analysis.

II. Modeling Of Hybrid Slit-Friction Dampers

The steel plate slit damper is composed of many vertical strips as shown in Fig. 1. The in-plane stiffness of the slit damper subjected to horizontal shear force can be obtained as follows based on the assumption that the ends of the narrow strips are fully restrained from rotation:

$$k_d = n\frac{12EI}{l_o^{\,3}} = n\frac{Etb^3}{l_o^{\,3}} \quad (1)$$

where n = number of strips, t = thickness of strips, b = width of strips, and l_o = length of the vertical strip. Chan and Albermani [1] derived the yield strength of a slit damper assuming elastic–perfectly-plastic behavior, which is summarized as follows. When displacement is large, plastic hinges form at both ends of the strip with the full plastic moment obtained by multiplication of the yield stress and the plastic section modulus:

$$M_p = \sigma_y \frac{tb^2}{4} \quad (2)$$

From the equivalence of the internal work, $P_y\delta_p$, and the external work, $2nM_p\theta_p$, where δ_p is the plastic displacement, $l_0\theta_p$, and θ_p is the plastic rotation, the yield force of the slit damper, P_y, can be obtained as follows:

$$P_y = F_{y,slit} = \frac{2nM_p}{l_0} = \frac{n\,\sigma_y\,tb^2}{2l_0} \quad (3)$$

The yield stress of the slit damper used in this study is 325 MPa, the thickness of the strip t is 20 mm, the length of the slit l_o is 200 mm, and the number of strip n is 9. The width of the strip b is varied from 15 mm to 20 mm..

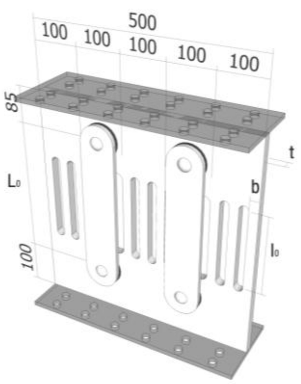

Fig. 1 Configuration of a hybrid slit-friction damper

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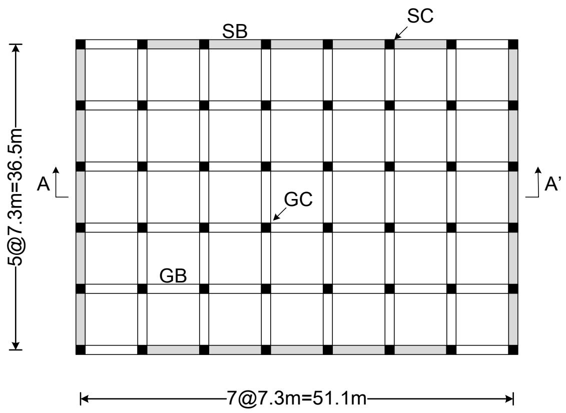
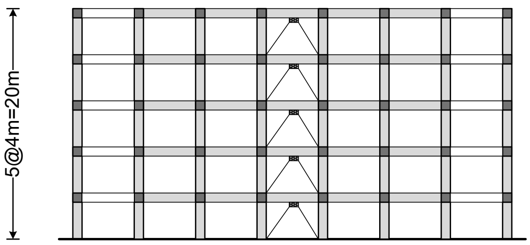
III. Design of Analysis Model Structures

The prototype analysis model structure is a five-story RC frame structure assumed to be located in downtown Los Angeles. Structural members were designed using ACI 318 [5] and the design seismic load was determined based on ASCE/SEI 7-10 [6]. The perimeter frames were designed as special moment frames and the internal moment frames were designed as gravity load-resisting frames. Fig. 2 shows the structural plan and the elevation view of the model structure. For gravity loads, the dead and live loads of 7.0 kN/m2 and 1.92 kN/m2 were used, respectively. The design seismic load was computed based on the design spectral response acceleration parameters SDS=0.73g and SD1=0.60g..



(a) Plan view



(b) Elevation view

Fig. 2 Configuration of 5-story analysis model structure

IV. Design Of A Structure With Hybrid Slit-Friction Dampers

ASCE/SEI 7-10 specifies nonlinear static and dynamic analyses, response spectrum analysis, and equivalent lateral force procedure for design of a structure with energy dissipation devices. In this study the prototype five-story special moment frame was redesigned using hybrid dampers following the response spectrum analysis procedure of the ASCE/SEI 7-10. The dampers were installed at the center bay of the structure as shown in Fig. 2. The design process of the structure with damping devices is as follows: the effective ductility demand of the seismic force resisting system is assumed and the effective damping at the design displacement of the structure with damping system is computed. Then using Table 18.6-1 of ASCE/SEI 7-10 the numerical coefficient for damped response modification factor is obtained, and the validity of the design base shear and the ductility factor assumed in the beginning of the design stage is verified.

V. Seismic Performance Evaluation of Model Structures

Non-linear analyses of the model structures were carried out using the program code Perform-3D (2006). The moment-rotation relationships of the columns and beams were modeled using the 'FEMA column and beam, concrete type' elements provided in the Perform-3D. The ultimate strength of concrete is 27 MPa and the tensile strength of re-bars is 400 MPa. The damping ratio was assumed to be 5% of the critical damping in all vibration modes.

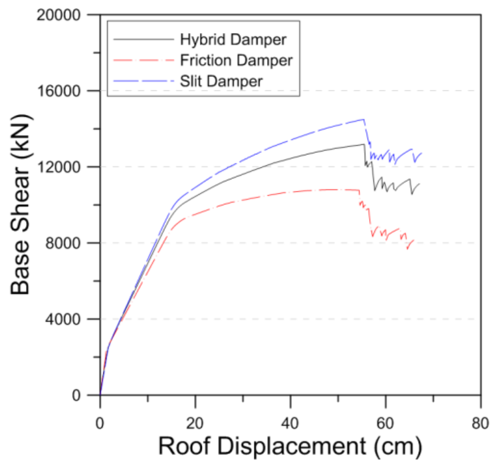


Fig. 5 Pushover analysis results of the 5-story analysis model structures

The lateral load pattern was determined to be proportional to the fundamental mode shape of the model structures. Fig. 3 depict the pushover curves of the model structure designed using 75% of the design base shear plus hybrid dampers, respectively. It can be observed that, as expected, the structure with dampers showed smaller initial stiffness than the structure without dampers. In the structure with dampers the first plastic hinge formed in the first story columns at the smaller load. Even though the strength of the prototype structure at the maximum inter-story drift of 2% of the story height is slightly higher than that of the damped structure, the opposite is true in the strengths at the maximum inter-story drift of 4% of the story height. Even though the damped structure was designed with only 75% of the design base shear of the prototype structure, the maximum strengths of the prototype and the damped structure are quite close to each other.

Figure 4 depicts the plastic hinge formation in the analysis model structures at the maximum inter-story drift of 2% of the story height. As the original structure without the dampers was designed to meet the weak beam – strong column requirement of ACI 318 code, plastic hinges first formed at the beams and were subsequently spread to the first story columns. In the structure with hybrid slit-friction dampers the formation of the plastic hinges is similar to that of the original structure except that no plastic hinge was observed in the second story beams and plastic hinges formed in the first story columns only at the center bay where the damper was installed. It was observed that in both model structures the rotations of the plastic hinges were within the IO (Immediate

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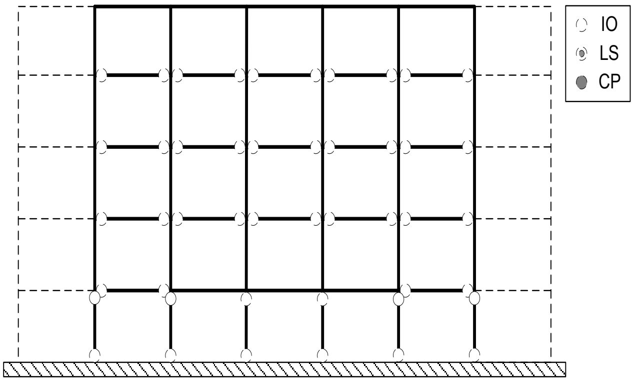
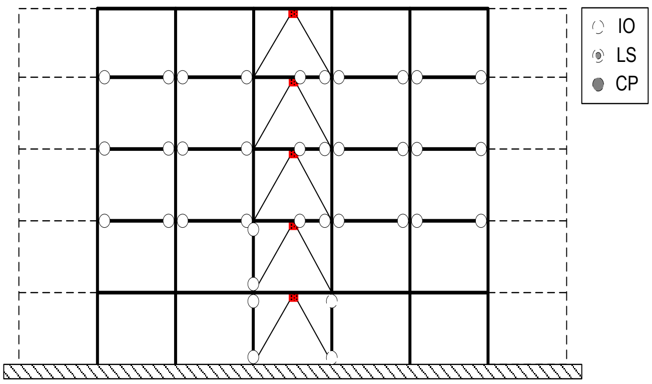
Occupancy) limit state specified in the ASCE/SEI 41-06.



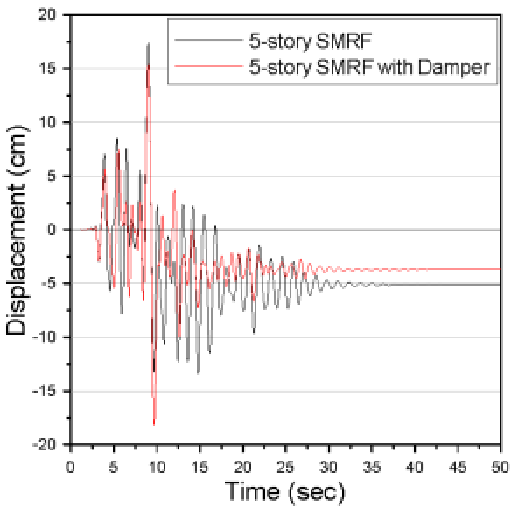
(a) Prototype structure



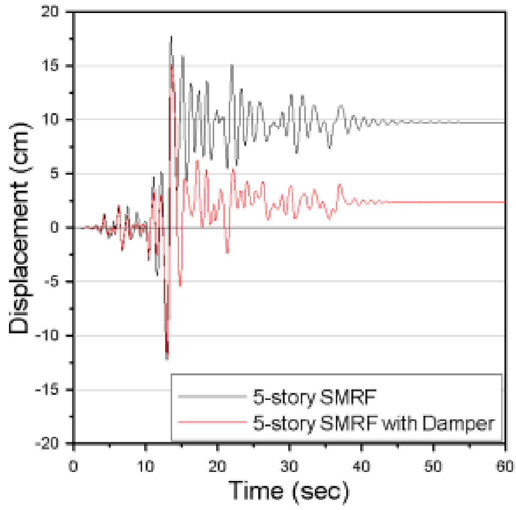
(b) Damped structure

Fig. 4 Plastic hinge formation at the maximum story drift ratio of 2%

Figure 5 shows the roof displacement time histories of the prototype and the damped structures subjected to the ground motions which are obtained from the PEER-NGA Database. It can be observed that, even though the maximum displacements of the two systems turned out to be similar to each other, the structure with hybrid dampers experienced less permanent displacement compared with the structure without the dampers.



(a) Northridge



(b) Superstition Hills

Fig. 5 Nonlinear dynamic analysis results

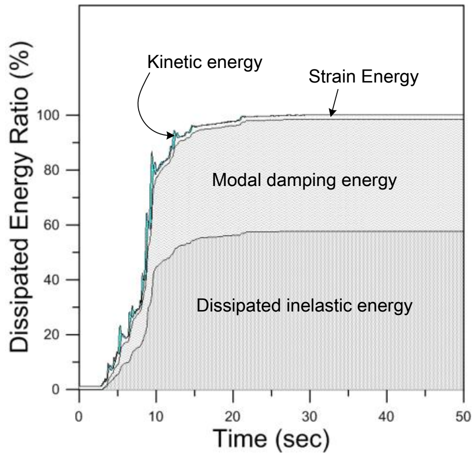


Fig. 6. Energy dissipation in the model structure subjected to Northridge earthquake

Figure 6 depicts the energy dissipation time histories in the model structures subjected to Northridge earthquake. It can be noticed that in the prototype structure about half the input seismic energy was dissipated by inelastic deformation of structural elements and the other half of the energy was dissipated by the inherent modal damping. In the structure with the dampers damage in the structural members was significantly reduced compared with the damage observed in the structure designed without the dampers. The hysteretic energy dissipated by the dampers turned out to be 57% of the dissipated hysteretic energy in the system. Figure 10 compares the dissipated energy in the model structures subjected to the Northridge earthquake with its spectral acceleration at the fundamental natural period of the model structure varied from 0.5g to 1.0g. No plastic hinge was observed at the spectral acceleration smaller than 0.5 g. In the damped structure it can be observed that as the spectral acceleration increases the portion of the energy dissipated by the beams and the columns gradually increases. However even at the spectral acceleration of 1.0 g the energy dissipated by the dampers exceeded 70 % of the total dissipated energy..

VI. Conclusion

This study investigated the seismic performance of a hybrid passive energy dissipation device composed of a friction damper and a steel slit damper. The effect of the device was verified by nonlinear dynamic analysis and fragility analysis. The analysis results showed that the dissipated inelastic energy was concentrated in the hybrid dampers and the damage in structural members was greatly reduced. It was also observed that, even though the maximum displacements were similar to each other, the residual displacement was significantly reduced in the structure with hybrid dampers..

Acknowledgment

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